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Weak Neutral Currents and Photoproduction of Lepton Pairs

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ABSTRACT

We have explored the consequences of weak neutral currents in the

photoproduction of lepton pairs at high energies. Specifically, we have

calculated the effects of the parity nonconserving interference between the

weak amplitude and the purely electromagnetic Bethe-Heitler amplitude.

This interference contributes to an asymmetry between the lepton pairs and,

in addition, the leptons acquire a longitudinal polarization. Numerical results

are presented for the Weinberg-Salam model and are typically a few percent

in magnitude.

We have calculated the effects of weak neutral currents in the photoproduction of lepton pairs at high energies:

$$\gamma(q) + N(P) \rightarrow \ell^{+}(p_{+}) + \ell^{-}(p_{-}) + X \qquad . \qquad (1)$$

While weak neutral currents have been observed in high energy neutrino scattering,[1] so far their couplings to charged leptons have not been established. In particular, the search for parity nonconserving effects in atomic Bi has not detected any signal[2] at the level expected in the Weinberg-Salam model[3] which has been rather successful in explaining the neutrino scattering data.[1]

The photoproduction of lepton pairs, which we consider here, has the advantage that it is sensitive to parity nonconserving couplings of the neutral current to both the charged leptons and to the hadrons, while the atomic Bi experiment primarily measures only the axial vector neutral current coupling to electrons. The calculations reported here are most closely related to previous studies of the deep inelastic scattering of polarized leptons:[4,5] $\ell^{\pm} + N \rightarrow \ell^{\pm} + X$. In both processes the neutral current effects become significant at high energies such as are available at Fermilab and the CERN SPS.

Four Feynman diagrams have been calculated: two giving the purely electromagnetic amplitude in which a photon is exchanged between the target and the lepton pair, and two giving the weak amplitude in which a neutral vector boson is exchanged between the target and the lepton pair. A representative diagram is shown in Fig. 1. We have computed the square

of the purely electromagnetic amplitude and its interference with the weak

amplitude neglecting the lepton mass. We have verified our results for the

purely electromagnetic part by comparing with the work of Drell and Walecka.[6]

The rather lengthy derivation of the formulas will be given in detail elsewhere

where we treat the completely general case of arbitrary vector and axial

vector couplings of the weak neutral current to charged leptons and hadrons.

In the calculation presented here we have chosen the particular neutral

current couplings given by the Weinberg-Salam model and further have made

the approximation that $\left| k^2 \right| \ll M_Z{}^2$ where $k = P - P_f$ (see Fig. 1) and M_Z

is the mass of the neutral weak intermediate boson. Further we have assumed

the Callan-Gross relations

$$\nu W_2 = 2Mx W_1 \tag{2}$$

$$\nu R_2 = 2Mx R_1 \tag{3}$$

where $\nu = -P \cdot k / M$, M is the target mass and $x = -k^2 / 2M\nu$ is the usual scaling

variable. W_1 and W_2 are the conventional structure functions appearing in

the matrix element of the product of two hadronic electromagnetic currents.

R_1 and R_2 are the analogous structure functions in the matrix element of

the symmetric product of the hadronic weak current and the hadronic neutral

current.[7]

Two neutral current effects have been calculated: the asymmetry A

between the leptons, ℓ^+ and ℓ^-, and their longitudinal polarizations

$\langle\lambda_+\rangle = -\langle\lambda_-\rangle$. Under the above assumptions we find that the asymmetry

is given by

$$A = \frac{d\sigma(p_+, p_-, \ldots) - d\sigma(p_-, p_+, \ldots)}{d\sigma(p_+, p_-, \ldots) + d\sigma(p_-, p_+, \ldots)}$$

$$= -\frac{G_F}{\sqrt{2}\,e^2}\left(\frac{xR_3}{W_2}\right)\frac{N}{D} \qquad , \qquad (4)$$

and that the polarization of ℓ^+ is

$$\langle\lambda_+\rangle = \frac{d\sigma(\lambda_+ = 1, \ldots) - d\sigma(\lambda_+ = -1, \ldots)}{d\sigma(\lambda_+ = 1, \ldots) + d\sigma(\lambda_+ = -1, \ldots)}$$

$$= -\frac{G_F}{\sqrt{2}\,e^2}\;\frac{R_2}{W_2}\;k^2 + (1 - 4\sin^2\theta_W)A \qquad . \qquad (5)$$

The kinematical factors N and D are the following:

$$N = q \cdot \Delta(P \cdot k\ell^2 - P \cdot qk^2) + \ell \cdot kP \cdot \Delta k^2 \qquad (6)$$

$$D = P \cdot \Delta q \cdot \Delta - P \cdot q\ell \cdot q + \tfrac{1}{2}\ell^2(P \cdot k + k^2\,\frac{M^2}{P \cdot k})$$

$$+ \frac{k^2}{2P \cdot k}\left[(P \cdot q)^2 + (P \cdot \Delta)^2\right]$$

$$+ \left[\frac{M^2}{P \cdot k} + 2\,\frac{P \cdot k}{k^2}\right]\left[(q \cdot p_+)^2 + (q \cdot p_-)^2\right] \qquad (7)$$

where $\ell = p_+ + p_-$ and $\Delta = p_- - p_+$. The structure function R_3 is the one

arising from the interference between the electromagnetic current and

the weak neutral axial vector current.[7]

For the structure functions we have assumed the quark-parton model

and in our numerical calculations we have used the quark distribution functions

given by Barger and Phillips.[8] For the remaining parameter, the Weinberg

angle, we have taken[1] $\sin^2 \theta_W = 0.3$.

In Figs. 2 and 3 we present numerical results for the polarization

$\langle \lambda_+ \rangle$ and asymmetry A for the two different kinematical configurations i

indicated in the figure captions. The angles $\theta_\pm$ are the polar angles between

$\ell^\pm$ and the photon beam direction while ϕ is the azimuthal angle between ℓ^+

and ℓ^-. Of course, E_γ, E_+ and E_- are the laboratory energies of the incident γ,

ℓ^+ and ℓ^-, respectively.

From Figs. 2 and 3 it is apparent that the effects are of the order of

a few percent in all cases. At least for $E_\pm \ll E_\gamma$ both $\langle \lambda_+ \rangle$ and A vary

approximately linearly with E_+ and E_- and are roughly proportional to E_γ.

Obviously, the observation of $\langle \lambda_+ \rangle$ is of much greater importance than

A since $\langle \lambda_+ \rangle$ is a clear signal for parity nonconservation. There are higher

order purely electromagnetic contributions to A but there are none to $\langle \lambda_+ \rangle$.

From the point of view of the feasibility of the experiment it is encouraging

that polarizations of a few percent persist even at relatively low energies E_+.

Thus it may be possible, for example, to stop a slow μ^+ and detect its

longitudinal polarization through the backward-forward asymmetry of the e^+ in the decay $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$.

Finally, we emphasize the importance of searching for neutral current effects in the photoproduction of lepton pairs. Unlike the atomic Bi experiments, the signals in this process survive even though the neutral current couplings of the charged leptons may be parity conserving. At high energies one expects to observe parity nonconservation arising from the hadronic vertex; i.e., terms proportional to R_3 in $<\lambda_+>$.

REFERENCES

[1] For a recent summary, see the report of B. W. Lee at the Aachen Neutrino Conference, FERMILAB-Conf-76/61-THY preprint.

[2] L. L. Lewis, et al., APS Bulletin $\underline{22}$, 62 (1977); D. C. Soreide, et al., Phys. Rev. Letters $\underline{36}$, 352 (1976); M. W. S. M. Brimicombe, et al., J. Phys. $\underline{B9}$, L237 (1976).

[3] S. Weinberg, Phys. Rev. Letters $\underline{19}$, 1264 (1967); A. Salam, in Elementary Particle Theory: Relativistic Groups and Analyticity (Nobel Symposium No. 8), edited by N. Svartholm (Almqvist and Wiksell, Stockholm, 1968), p. 367.

[4] E. Derman, Phys. Rev. $\underline{D7}$, 2755 (1973).

[5] S. M. Berman and J. R. Primack, Phys. Rev. $\underline{D9}$, 2171 (1974).

[6] S. D. Drell and J. D. Walecka, Ann. Phys. (N.Y.) $\underline{28}$, 18 (1964).

[7] We have adopted the notation of ref. 4 for the structure functions.

[8] V. Barger and R. J. N. Phillips, Nucl. Phys. $\underline{B73}$, 269 (1974).

FIGURE CAPTIONS

Fig. 1:   Typical Feynman diagram for the electromagnetic and weak

amplitudes for the photoproduction of lepton pairs.

Fig. 2:   For $\theta_+ = 30^\circ$, $\theta_- = 5^\circ$, $\phi = 180^\circ$ and $E_\gamma = 150$ GeV the asymmetry

A and the polarization $<\lambda_+>$ $\left[$Eqs. (4) and (5)$\right]$ in % as a function of

E_-.   The continuous and broken lines correspond to $E_+ = 2.5$
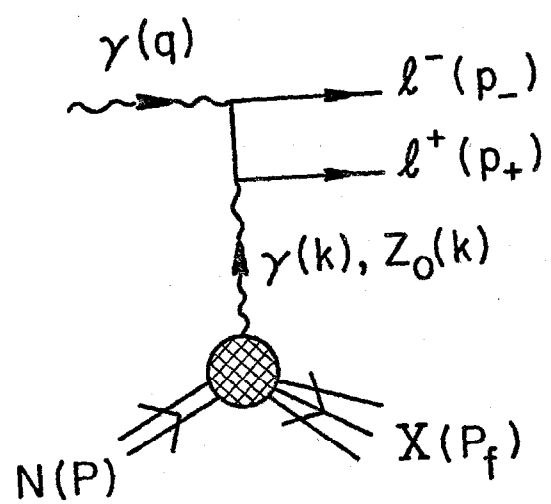
GeV and 5 GeV, respectively.

Fig. 3:   For $\theta_+ = 30^\circ$, $\theta_- = 3^\circ$, $\phi = 180^\circ$ and $E_\gamma = 200$ GeV the asymmetry

A and the polarization $<\lambda_+>$ $\left[$Eqs. (4) and (5)$\right]$ in % as a function

of E_-.   The continuous and broken lines correspond to $E_+ = 2.5$ GeV

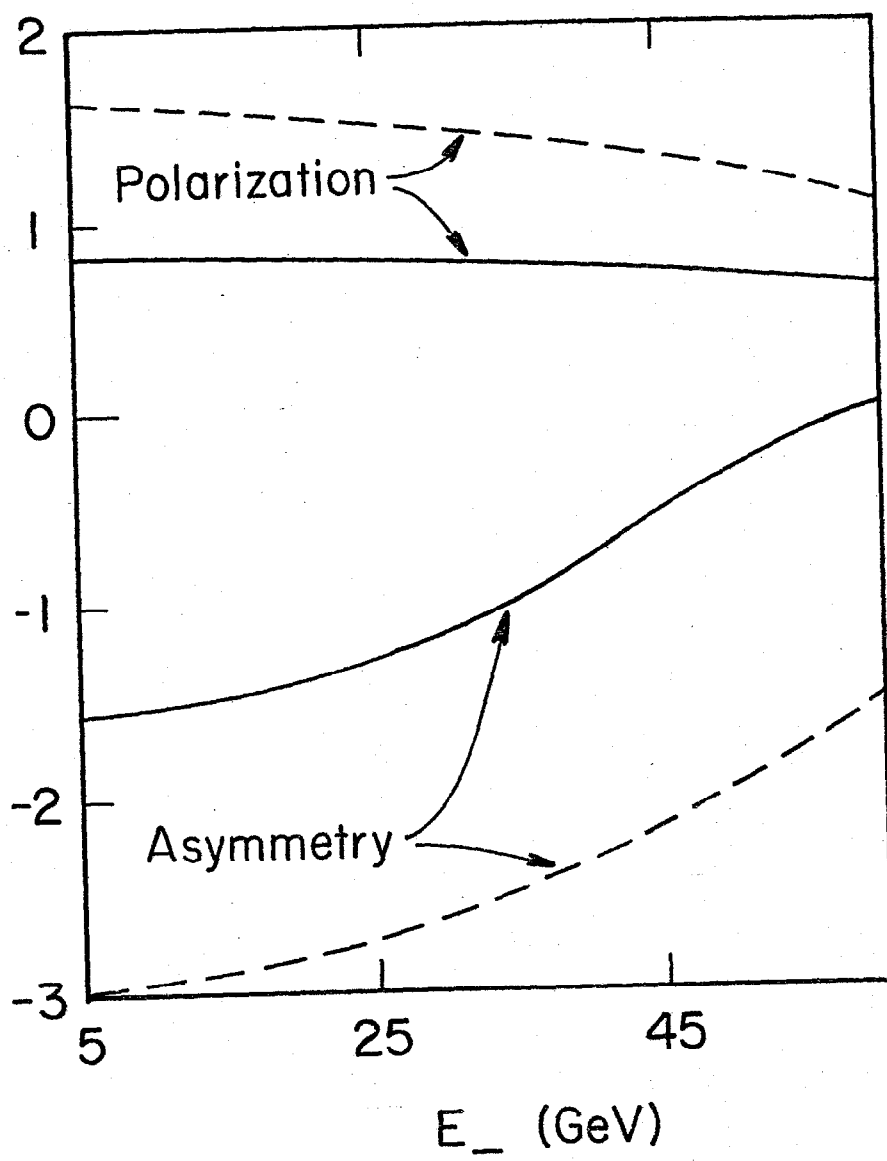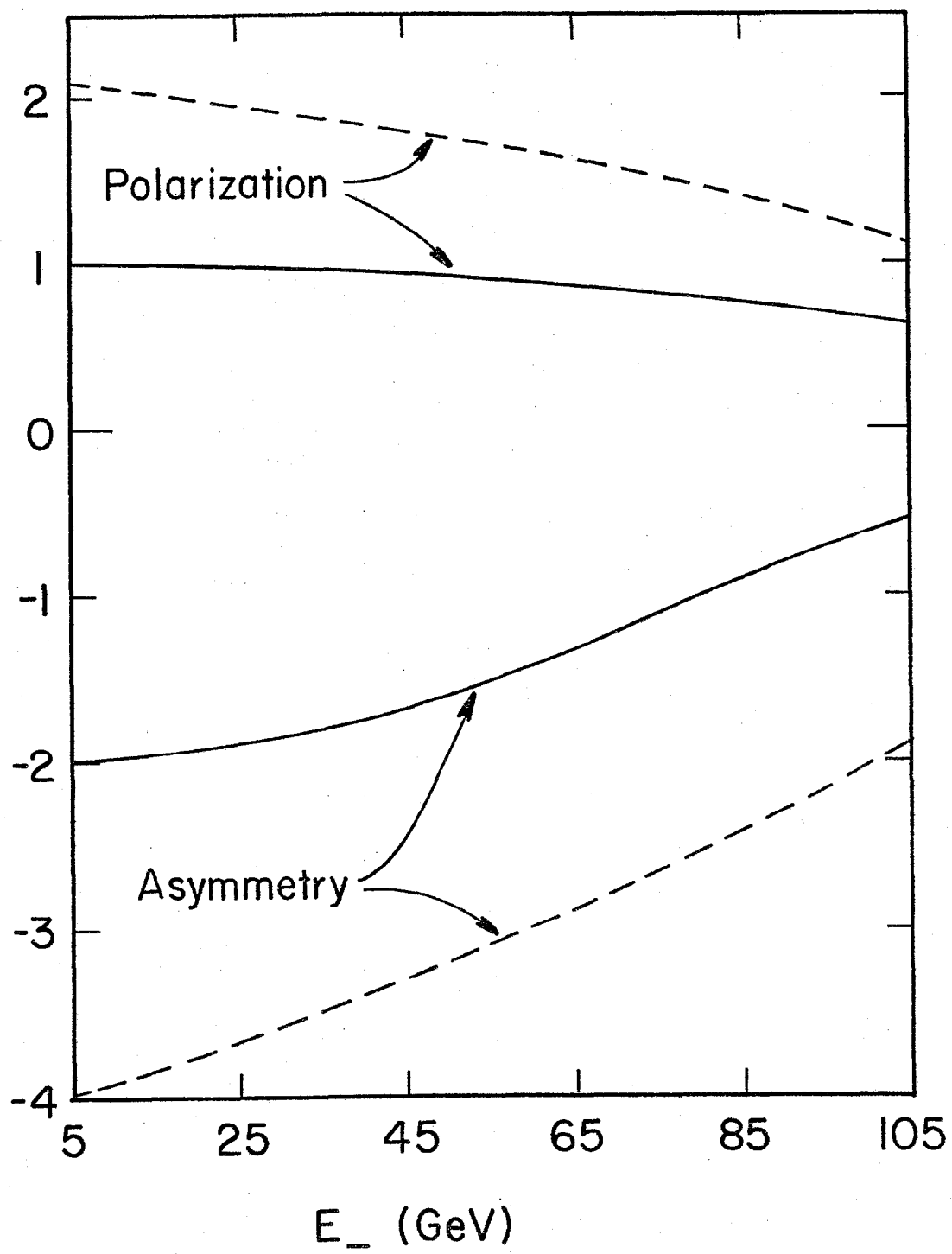and 5 GeV, respectively.

Fig. 1

Fig. 2

Fig. 3